

New Finite Element Models and Seismic Analyses of the Telescopes at W.M. Keck Observatory

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ABSTRACT

On 15 October 2006 a large earthquake damaged both telescopes at Keck observatory resulting in weeks of observing downtime. A significant portion of the downtime was attributed to recovery efforts repairing damage to telescope bearing journals, radial pad support structures and encoder subsystems. Inadequate damping and strength in the seismic restraint design and the lack of break-away features on the azimuth radial pads are key design deficiencies. In May, 2011 a feasibility study was conducted to review several options to enhance the protection of the telescopes with the goal to minimize the time to bring the telescopes back into operation after a large seismic event. At that time it was determined that new finite element models of the telescope structures were required to better understand the telescope responses to design earthquakes required by local governing building codes and the USGS seismic data collected at the site on 15 October 2006. These models were verified by comparing the calculated natural frequencies from the models to the measured frequencies obtained from the servo identification study and comparing the time history responses of the telescopes to the October 2006 seismic data to the actual observed damages. The results of two finite element methods, response spectrum analysis and time history analysis, used to determine seismic demand forces and seismic response of each telescope to the design earthquakes were compared. These models can be used to evaluate alternate seismic restraint design options for both Keck telescopes.

Keywords: Finite element model, Seismic analysis, Response spectrum analysis, Time history analysis, Earthquake, Optical telescope, Telescope structure, Keck

1. INTRODUCTION

The October 2006 Mauna Kea earthquake caused significant observatory damage and resulted in weeks of observing downtime. A significant part of the observatory downtime was attributed to recovery efforts to repair damage to telescope bearing journals, radial pad support structures, and encoder subsystems. Inadequate damping and strength in the seismic restraint design and the lack of break-away features on the azimuth radial pads are key design deficiencies. Keck decided to upgrade the structural support systems of both telescopes for survival-level earthquakes.

In May 2011, Simpson Gumpertz and Heger (SGH) completed a review of the seismic upgrade requirements and specifications for the Keck Telescopes, and performed a preliminary feasibility study for a new seismic restraint system. The preliminary feasibility study used a simple two-degree-of-freedom (two-DOF) analysis with estimated mass and stiffness values of three seismic restraint design options. The two-DOF analysis only gave a very rough estimate of the dynamic response of the telescope for three different seismic restraint design options. Based on the results obtained by SGH results, Keck Observatory performed a cost evaluation and found all three seismic restraint design options to have low benefit/cost ratios. Keck Observatory funded this study to develop finite element models of the two telescopes so that more detailed seismic analyses can be performed. With an improved mathematical representation of the telescope structure, the seismic response of the telescope can be reliably estimated to ensure all critical and high-value equipment (including instruments) will be protected in the event of a high acceleration event. Also, the finite element models developed in this effort can be used in future design upgrades and telescope performance studies.

This paper summarizes the development of finite element models of Keck I and Keck II Telescopes and the results of preliminary seismic analyses to predict the telescope's response to a survival-level earthquake. These models are to be later used to evaluate alternate seismic restraint design options.

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The work that SGH performed in this study includes the following:

- Develop finite element models of Keck I and Keck II Telescopes using information provided by Keck Observatory, including shop drawings, solid models, instrument mass tables, measurement of total weight, and photos of subassemblies of the two telescopes.
- Perform time history analyses of the two telescopes subjected to the recorded ground accelerations from the 2006 Mauna Kea earthquake and compare results to the observed damage.
- Perform modal analyses of the two telescopes and compare the calculated natural frequencies to the measured frequencies obtained from the servo identification study performed by Keck Observatory.
- Perform seismic response spectrum analyses of the two telescopes subjected to a survival-level earthquake.
- Perform time history analyses of the two telescopes subjected to seven sets of ground acceleration time histories for survival-level earthquake.

2. FINITE ELEMENT MODEL

Finite element models of Keck I and Keck II Telescopes were developed. Each telescope finite element model includes the elevation structure, yoke, Nasmyth and Cassegrain platforms, concrete pier, and the soil underneath. Figure 1 shows the overall views of the finite element models. ANSYS [1] APDL scripting language was used to develop the models. The information on the shop drawings, in solid models, and from measurements of the physical structure provided by Keck Observatory was used in developing the models.

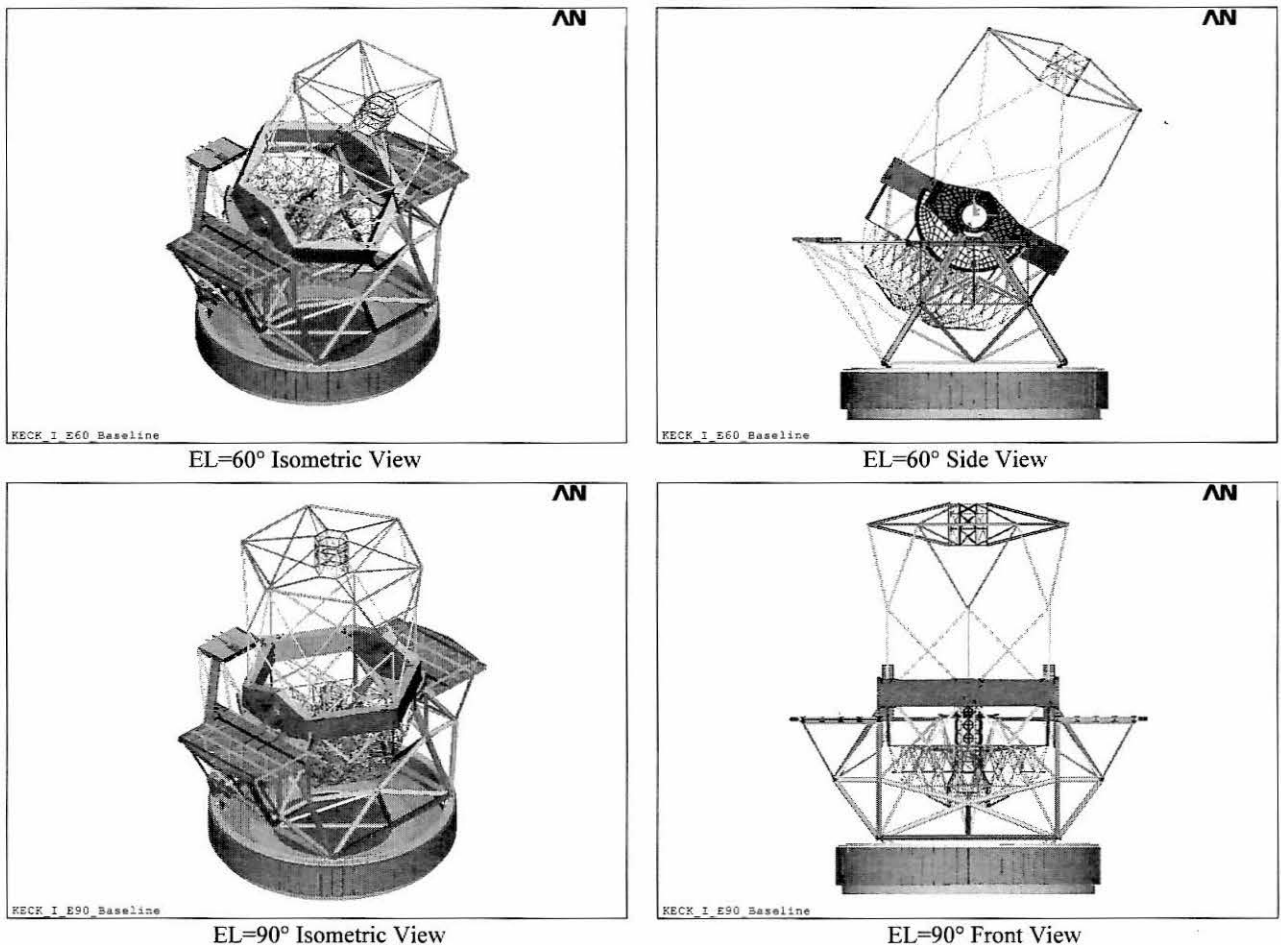


Figure 1. Finite Element Model of Keck I Telescope Structure

There are two coordinate systems in the models: global and optical coordinate systems. The global coordinate system is a Cartesian coordinate system where the origin is located at the intersection between the Elevation axis and Azimuth axis, the X-axis is collinear with the Elevation axis, the Z-axis is vertical pointing up, and the Y-axis is perpendicular to both X-axis and Z-axis using the right hand rule. The optical coordinate system is also a Cartesian coordinate system where the origin is located at the intersection between the Elevation axis and Azimuth axis, the X-axis is collinear with the Elevation axis, the Z-axis is along the optical axis pointing to sky, and the Y-axis is perpendicular to both X-axis and Z-axis using the right hand rule.

The elevation ring, concrete pier, and the Nasmyth and Cassegrain platform grating were modeled using shell elements. Thin shell elements were used to model the Nasmyth and Cassegrain platform grating to properly distribute the mass while not overly stiffening the structure.

All the other structural members were modeled using beam elements with appropriate cross-section dimensions based on specified steel shapes on the shop drawings. The elevation axis stub was modeled with beam elements with equivalent stiffness to match the physical stub shafts which consist of cylindrical plates with radial stiffeners.

Mass elements were used to model the non-structural instruments and mirrors. Spring elements were used to model the hydrostatic pads, drives, and soil underneath the concrete pier. Table 1 lists the stiffnesses of the spring elements used in the model. The stiffnesses of the hydrostatic pads were calculated using an oil film thickness of 90 microns. The tangential stiffnesses of the drives at the sector gears were calculated using a drive stiffness of 9.5×10^5 and 4.2×10^5 N-m/rad about the Azimuth axis and Elevation axis, respectively, for Keck I; and a drive stiffness of 9.8×10^5 and 3.1×10^5 N-m/rad about the Azimuth axis and Elevation axis, respectively, for Keck II. The stiffnesses of the three translational and three rotational soil springs were calculated based on the soil properties given in [2] and [3], and using methods described in [4]. The concrete pier was connected to the soil springs by a series of multipoint constraints from all nodes at the base of the pier to a single node at which the soil springs are connected.

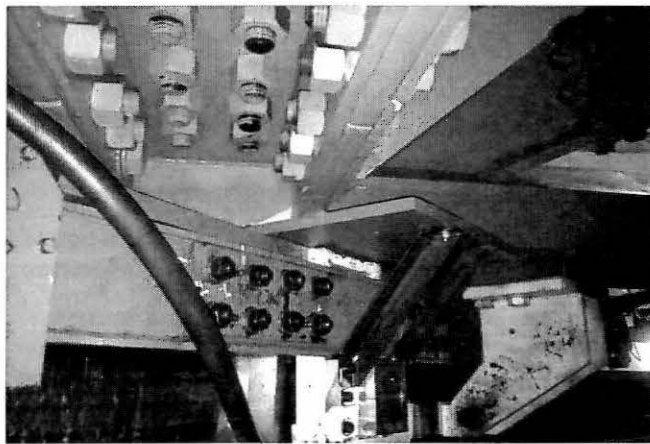
Table 1. Spring Stiffnesses used in Finite Element Model

Spring Type	Spring Orientation	Stiffness
Soil	Vertical	2.409×10^9 N/m
	Horizontal	2.000×10^9 N/m
	Rocking	1.327×10^{11} N-m/rad
	Torsion	1.885×10^{11} N-m/rad
Hydrostatic Pads	Azimuth Vertical	2.65×10^{10} N/m
	Azimuth Radial	1.67×10^9 N/m
	Elevation Radial	1.25×10^{10} N/m
Drives	Azimuth Tangential	Keck I = 1.70×10^8 N/m Keck II = 1.75×10^8 N/m
	Elevation Tangential	Keck I = 1.49×10^8 N/m Keck II = 1.10×10^8 N/m

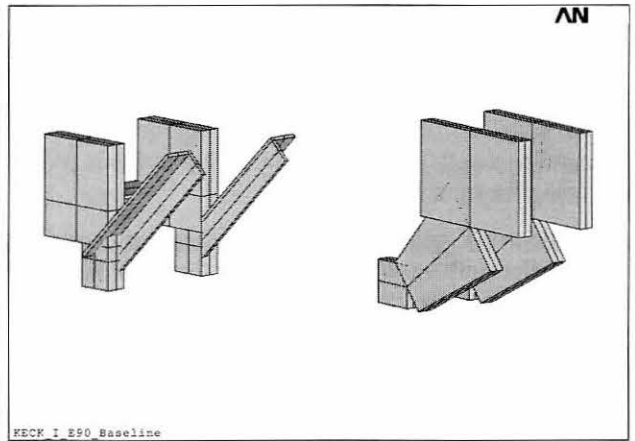
Fully fixed boundary conditions were applied at the node below the soil springs.

The spider tensioners, that support the secondary socket structure from the upper tube assembly, were pretensioned. In the model, a temperature drop was applied to develop the specified pretension forces in these spider tensioners. If the pretension forces in these members were not included in the model, the secondary socket would rotate about the optical axis, resulting in unrealistically low natural frequencies of the structure.

The finite element models for Keck I and Keck II are identical, except for the seismic restraint systems shown in Figures 2 through 3. The Keck I telescope has a support bracket for the radial hydrostatic pad at each connection point between the yoke and the Azimuth track, and a separate seismic restraint, or Earthquake Safety Bracket, at each of these locations. The contact between the Earthquake Safety Bracket and the Azimuth drive track was modeled with stiff spring elements. The Keck II telescope has a combined seismic restraint and radial hydrostatic pad bracket.

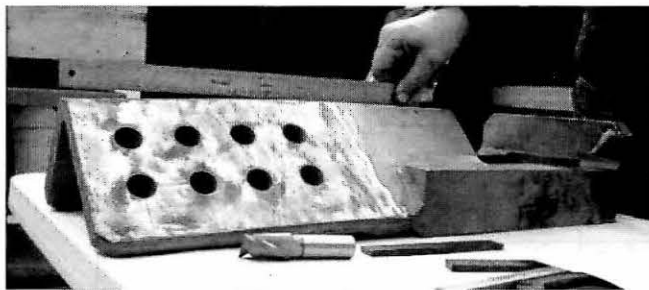


Photograph

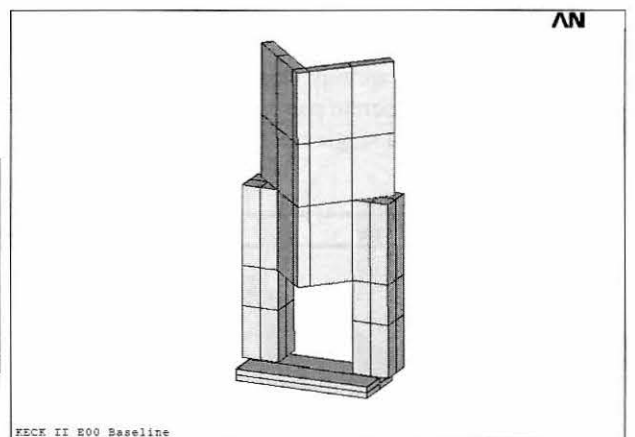


Modeled

Figure 2. Radial Hydrostatic Pad Bracket and Earthquake Safety Bracket for Keck I



Photograph



Modeled

Figure 3. Combined Bracket for Radial Hydrostatic Pad and Seismic Restraint for Keck II

The material properties used in the models are linear elastic. For steel, a modulus of elasticity of 200 GPa, a Poisson's ratio of 0.3, and a density of $7,850 \text{ kg/m}^3$ increased by 15% to $9,028 \text{ kg/m}^3$ to account for mass of connections were used. For concrete, a modulus of elasticity of 30 GPa, a Poisson's ratio of 0.2, and a density of $2,400 \text{ kg/m}^3$ were used. The Nasmyth and Cassegrain platform gratings weight 96.41 kg/m^2 and 97.28 kg/m^2 , respectively.

The elevation structure, consisting of the mirror cell, tube assemblies, elevation ring, spider tensioners, secondary socket, and associated instrument masses, was defined in the optical coordinate system to allow for adjustment of the elevation angle in 5° increments from horizon pointing at 0° to zenith pointing at 90° .

Table 2 shows the weight breakdown of the finite element model.

Weight of the steel structure had to be increased by 15% to better match the measured total weight. The model is probably light because of the connections are not modeled explicitly. One cannot identify exactly which part of the model is too light as a more-detailed measured weight breakdown was not available. Weight of the telescope has significantly increased over the years. Recent measured weight of the moving structure of 357 tons is more than two times the weight reported in [5] from 1985.

Table 2. Telescope Weight Breakdown

Subassembly	Modeled Mass (tons)	Ref. Mass (tons)
Elevation Structure	132.7	-
Steel Structure	97.7	-
Mirror Cell	12.0	-
Mirror Glass and Supports	20.6	29.6
Tertiary Tower	3.0	2.0
Secondary Socket	2.0	-
Top Ring and Spider Tensioners	4.5	3.4
Upper Tube Assembly	11.1	9.6
Lower Tube Assembly	9.9	-
Elevation Box + Drives	55.2	22.8
Elevation Structure Instruments	11.3	11.3
Yoke and Nasmyth Platforms	205.8	90.0
Yoke Steel Structure	141.9	-
Nasmyth Platforms Steel Structure	27.1	-
Nasmyth Platforms Deck	11.2	-
Cassegrain Platform Steel Structure	2.8	-
Cassegrain Platform Deck	0.9	-
Nasmyth Platform Instruments	21.5	21.5
Total Telescope Moving Weight	338.5	357.0

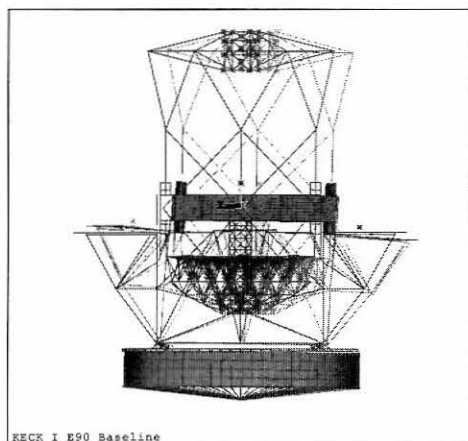
3. MODAL ANALYSES

Modal analyses were performed to compute the first ten natural frequencies of Keck I and Keck II Telescopes with the telescopes at elevation angles 0°, 60°, and 90°. Table 3 lists the results of the modal analyses for Keck I at elevation angle 90°. Figure 4 show the first lateral, first elevation, second elevation, and first azimuth modes of Keck I at elevation angle 90°.

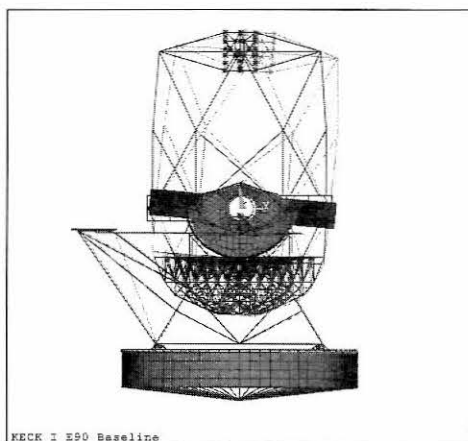
Table 3. Natural Frequency of First Ten Mode Shapes of Keck I at EL=90°

Mode	Frequency (Hz)	Mode Shape
1	3.25	1 st Lateral
2	3.47	1 st Elevation
3	4.31	2 nd Elevation
4	4.95	1 st Platform
5	5.07	2 nd Platform
6	5.60	1 st Azimuth
7	6.67	1 st Vertical
8	6.79	3 rd Platform
9	6.95	2 nd Lateral
10	7.15	3 rd Elevation

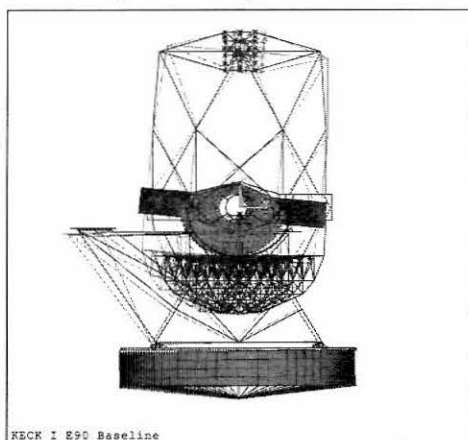
The calculated natural frequencies compare fairly well with the measured frequencies obtained from the servo identification study for Keck I shown in Figure 5, where the first locked rotor frequency for elevation are 3.5 Hz compared to 3.47 Hz from the modal analysis; and the first locked rotor frequency for azimuth are 5.1 Hz compared to 5.60 Hz from the modal analysis.



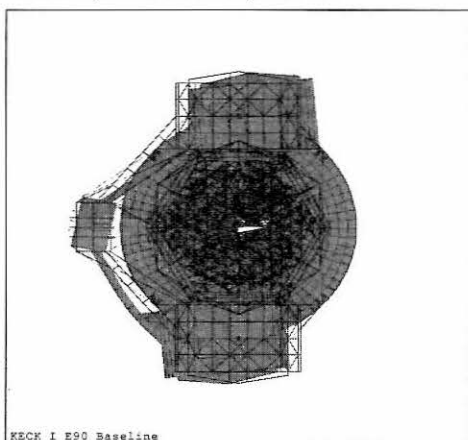
Mode 1, First Lateral, 3.25 Hz



Mode 2, First Elevation, 3.47 Hz

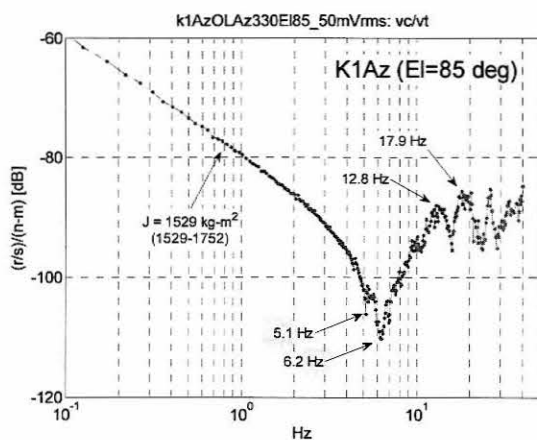


Mode 3, Second Elevation, 4.31 Hz



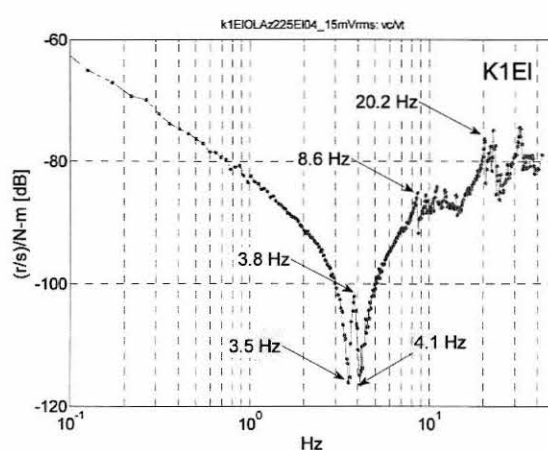
Mode 6, First Azimuth, 5.60 Hz

Figure 4. Mode Shape of Keck I at EL=90°



a)

Figure 5. a) 2011 Keck I Azimuth Response. b) 2011 Keck I Elevation Response



b)

4. TIME HISTORY ANALYSIS FOR 2006 MAUNA KEA EARTHQUAKE

Time history analyses were performed to compute the dynamic responses of Keck I and Keck II Telescopes when subjected to the 2006 Mauna Kea Earthquake shown in Figure 6. The finite element models of Keck I and Keck II were orientated in the same way that it was during the earthquake with the azimuth angles of 247.5° (from north) for Keck I and 67.4° for Keck II, as well as the elevation angle of 0° .

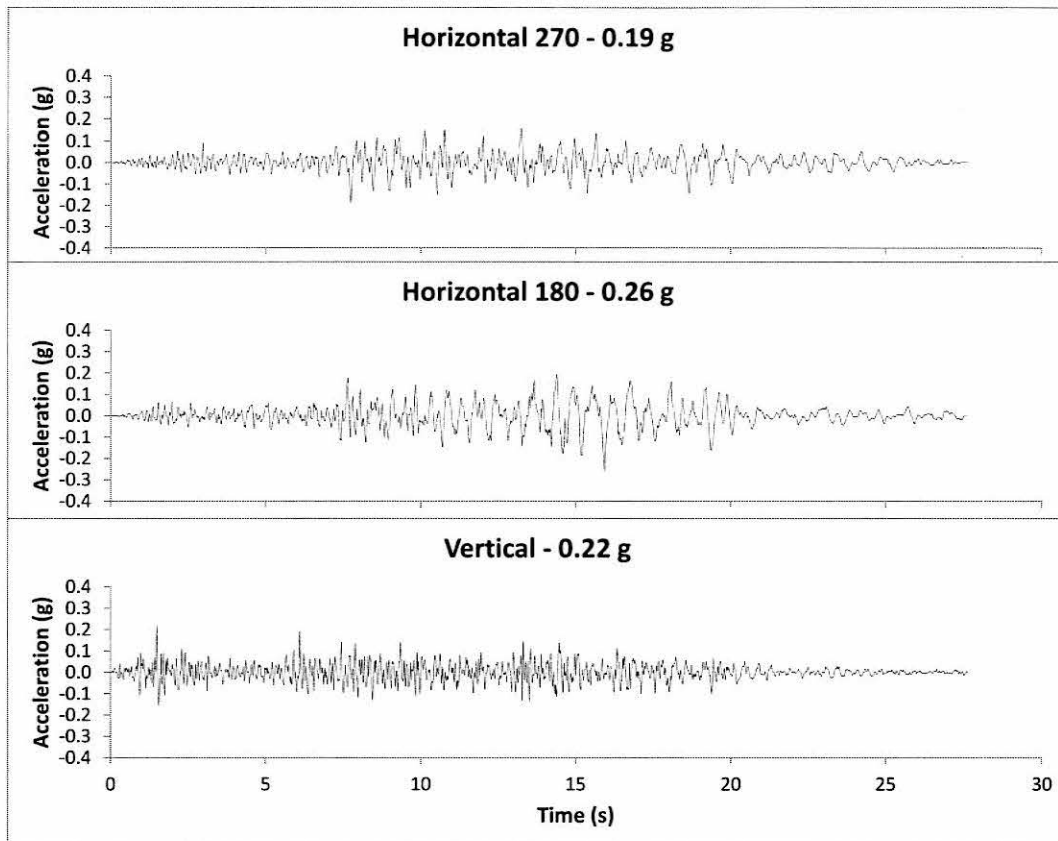


Figure 6. 2006 Hawaii Unscaled Acceleration Time History

Implicit time integration method was used to calculate the transient dynamic responses. In this preliminary study, the finite element models were linear-elastic models. The model does not include energy dissipation mechanisms, such as dashpots, inelastic material behavior, etc. In this study, Rayleigh damping was scaled to a target value at the lower (mass-proportional) and higher (stiffness-proportional) frequencies of interest. Figure 7 shows the two levels of damping considered, namely 0.5% and 2%. The 0.5% damping is selected to predict the response of a telescope structure with little to no damage, having stresses no more than half of the yield point, and the 2% damping is for a telescope structure having stresses at or just below the yield point.

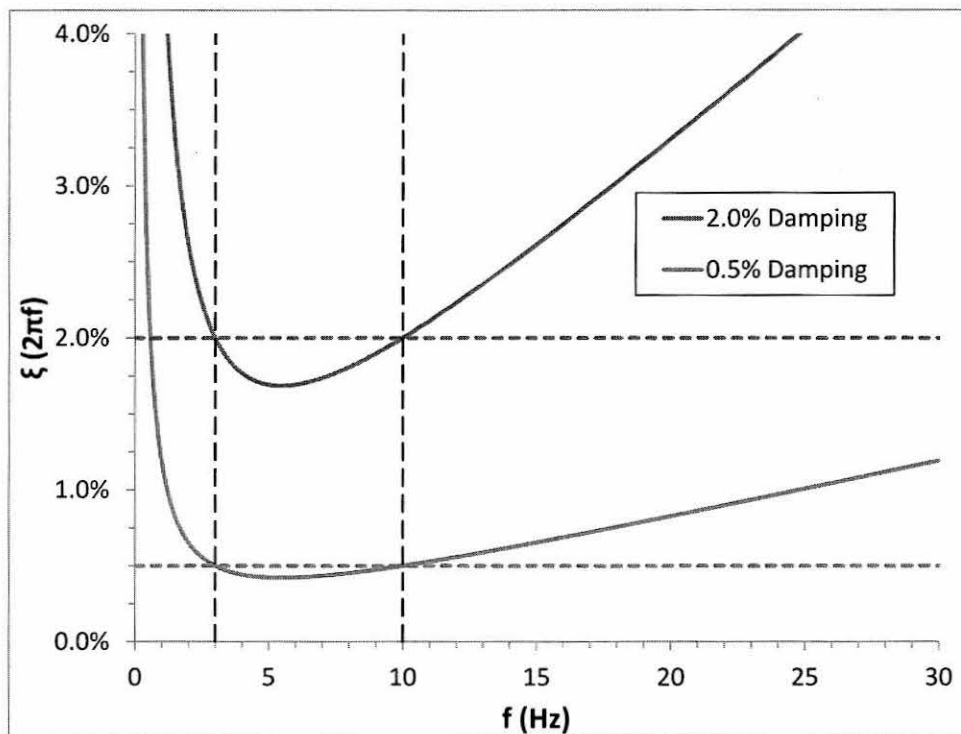


Figure 7. 0.5% and 2.0% Rayleigh Damping Curves

Tables 5 through 8 summarize the peak dynamic responses from the time history analyses for the 2006 Mauna Kea Earthquake. Tables 5 and 6 list the peak accelerations and displacements in the global coordinate system for the followings locations: (1) Primary Mirror, (2) Nasmyth Platform, (3) Cassegrain Socket, (4) Tertiary Mirror Socket, and (5) Secondary Mirror Socket. Table 7 lists the peak forces in the following components: (1) Keck I Azimuth Hydrostatic Radial Support, (2) Keck I Earthquake Safety Bracket, (3) Keck II Combined Bracket, (4) Azimuth Drive, and (5) Azimuth Hydrostatic Vertical Support. Table 8 lists the elastic strain in the Keck I Azimuth Hydrostatic Radial Support, Keck I Earthquake Safety Bracket, and Keck II Combined Bracket.

Table 8 shows very high strains in the AZ Hydrostatic Radial Supports in Keck I and the Combined Brackets in Keck II. If plasticity were included in the model, these components would have had permanent deformation. The strains in the Keck I Earthquake Safety Brackets are much less. Analysis predicts very little to no yielding in the Earthquake Safety Brackets. These results are consistence with the observed damage.

The calculated travels at the azimuth track for the 2006 Mauna Kea Earthquake are much less than the observed values of 11 mm because material plasticity and contact interaction at the supports were not included in the model.

5. SEISMIC GROUND MOTION

The Keck Telescopes are located on a cinder cone on top of Mauna Kea, Island of Hawaii, which is in a seismically active region. The site is underlain by volcanic cinder, mostly sand and gravel in size, which are generally medium dense. The cinders from depths of 5 ft (1.5 m) to approximately 35 ft (10.7 m) have average compressional and shear wave velocities of 1,130 and 610 ft/s (344 and 186 m/s), respectively [2]. The compacted backfill material around the Coude Tunnel is estimated to have an average shear wave velocity of 900 ft/s (274 m/s) [3].

The governing building code for these telescopes is the Hawaii County Code [6]. In July 2012, the Hawaii County Code adopted the IBC 2006 [7] as the building code with some amendments. The IBC 2006 in turn references the ASCE 7-05 Standard [8] for defining the design seismic ground motion. Based on the above soil properties, the site was classified in accordance with the building code as Site Class D. The corresponding 5% damped design spectral response acceleration at short periods, S_{DS} , and at 1 sec period, S_{D1} , are 1g and 0.6g, respectively. Figure 8 shows the building code design response spectrum which is defined as the survival-level earthquake in the seismic requirements. The 0.5% and 2%

damped design response spectra were computed by scaling the 5% damped spectral using Newmark and Hall median amplification factors [9].

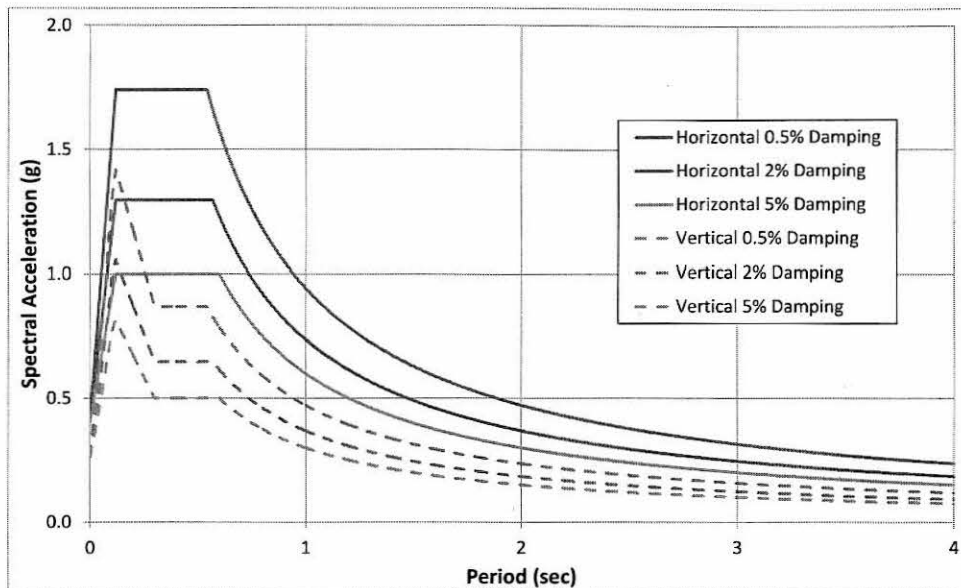


Figure 8. Horizontal and Vertical Design Response Spectra

In 2010, URS conducted a site-specific seismic hazard assessment for the proposed Thirty Meter Telescope site, north of the summit of Mauna Kea [10]. The assessment consisted of a probabilistic seismic hazard analysis (PSHA) to compute 5% damped horizontal component response spectra corresponding to average return periods of 10, 200, 1,000, and 2,475 yrs. Deterministic analysis was employed to obtain the corresponding vertical component response spectra. The URS report contains seven sets of acceleration time histories that are compatible with the 10 year response spectra and another seven sets of time histories that are compatible with the 1,000 year response spectra.

To obtain the vertical design response spectra (also shown in Figure 8) for this study, the horizontal building code design response spectra were multiplied by the ratio of vertical component to horizontal component response spectral accelerations determined from URS's study [10].

In this study, seven sets of earthquake time histories were used since the building code allows averaging the seismic responses from the seven sets. The seven sets of acceleration time histories selected by URS for 1,000 year ground motion (before modification) were scaled in accordance with ASCE 7-05 Section 16.1.3 to obtain building code (survival level) design acceleration time histories. The methodology used in the scaling is as follows:

- For each set of time histories, the response spectra of the two horizontal components were computed and combined using SRSS method. The combined horizontal component response spectrum was scaled such that the mean value of all points between frequencies 0.5 Hz and 25 Hz (i.e., between periods 0.04 sec to 2 sec) matches that of 1.3 times the design response spectrum.
- All seven sets of time histories were then scaled with a single scale factor such the final average of all seven sets is not less than 1.3 times the design response spectrum by more than 10% for periods between 0.2T and 1.5T (i.e., periods between 0.05 s to 0.375 s, or frequencies between 2.67 Hz and 20 Hz) where the period of the structure, T, was conservatively selected as 0.25 s.
- The vertical component time histories were scaled to the survival-level earthquake using the same scale factors.

Table 4 lists the selected acceleration time histories, the corresponding scale factors, and the peak accelerations. Figure 9 shows the response spectra of the scaled time histories in the horizontal and vertical directions respectively.

Table 4. Earthquake Time History Scale Factors

Earthquake	Scale Factor
1979 Imperial Valley	1.055
1980 Mammoth Lake	1.003
1983 Hawaii	1.082
1989 Loma Prieta	0.875
1992 Landers	3.019
1994 Northridge	1.321
2006 Hawaii	2.067

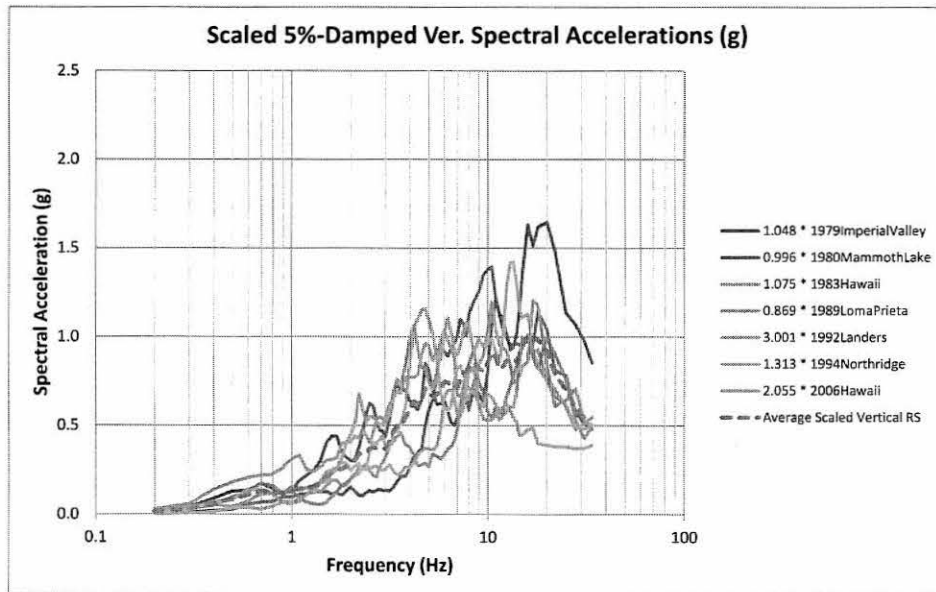
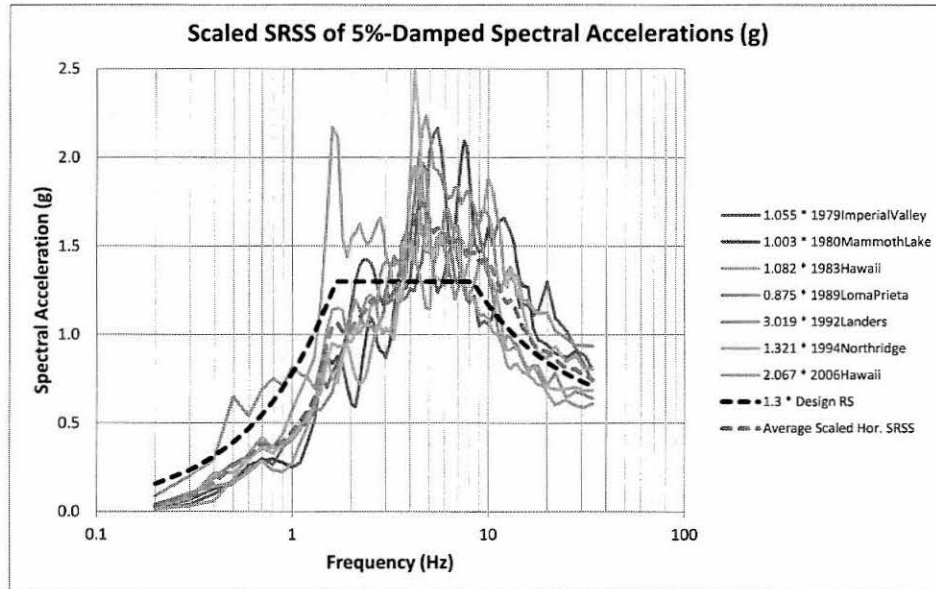


Figure 9. 5% Damped Response Spectrum of Survival Level Time Histories

6. RESPONSE SPECTRUM ANALYSES

A response spectrum is a plot of the peak response (displacement, velocity or acceleration) of a series of oscillators (single degree-of-freedom mass/spring systems) of varying natural frequency that are forced into motion by the same time history ground motion. The resulting plot can then be used to calculate the response of a structure subjected to the seismic ground motion if the natural frequency of the structure is known.

Response spectra can also be used in assessing the response of linear systems with multiple modes of oscillation (multi-degree-of-freedom systems), though they are only accurate for low levels of damping. A modal analysis is first performed to extract the natural frequencies and mode shapes of the structure. For each mode, the response of the structure is first determined from the response spectrum and the mode shape. The responses from all modes within the frequency range of interest are then combined to estimate the total response of the structure. Sufficient modes must be used in the modal response spectrum analysis such that the cumulative mass participation factors are over 90%.

The results of a modal response spectrum analysis can be different from those obtained from a time history (transient dynamic) analysis, because the phase information is lost in the process of generating the response spectrum. Also, modal response spectrum analysis is only suitable for linear systems. Nonlinear time history analysis is needed to capture any nonlinear behavior such as material yielding, sliding at the azimuth track, and effects of any energy dissipating devices. Nevertheless, modal response spectrum analysis is a simple and efficient way to estimate the peak seismic response of the telescope structure with linear behavior.

In this study, modal response spectrum analyses were performed to obtain preliminary results for the survival-level seismic design events. The seismic acceleration in the two horizontal and the vertical directions were applied using the 0.5% and 2% damped design spectral response accelerations as input for Keck I and Keck II with the telescopes at elevation angles 0°, 60°, and 90°. The analyses include modes up to 30 Hz such that the cumulative mass participation factor of over 90% in the horizontal and vertical directions. Figure 10 shows the cumulative mass participation factors in the horizontal and vertical directions. The SRSS method was used for modal combination and for combining the responses from the three directions.

Tables 5 through 8 summarize the peak dynamic responses from our modal response spectrum analyses together with those from the time history analyses for the 2006 Mauna Kea Earthquake and survival-level earthquake. In general, the peak seismic responses for 0.5% damped structure are approximately 1.3 times higher than those for 2% damped structure. The peak seismic responses of Keck I are about the same as those of Keck II. The peak seismic responses of the elevation structure change with elevation angle. Table 5 shows the peak acceleration is about 4 to 5 g at secondary mirror socket and Nasmyth platform at the instrument support, 3.5 to 4.5 g at Cassegrain socket and Tertiary Mirror socket, and 3 to 4 g at the Primary Mirror for 2% damped structure. Table 8 shows that survival-level earthquake will cause damage to the Keck I Hydrostatic Radial Supports and Earthquake Safety Brackets, and the Keck II Combined Brackets.

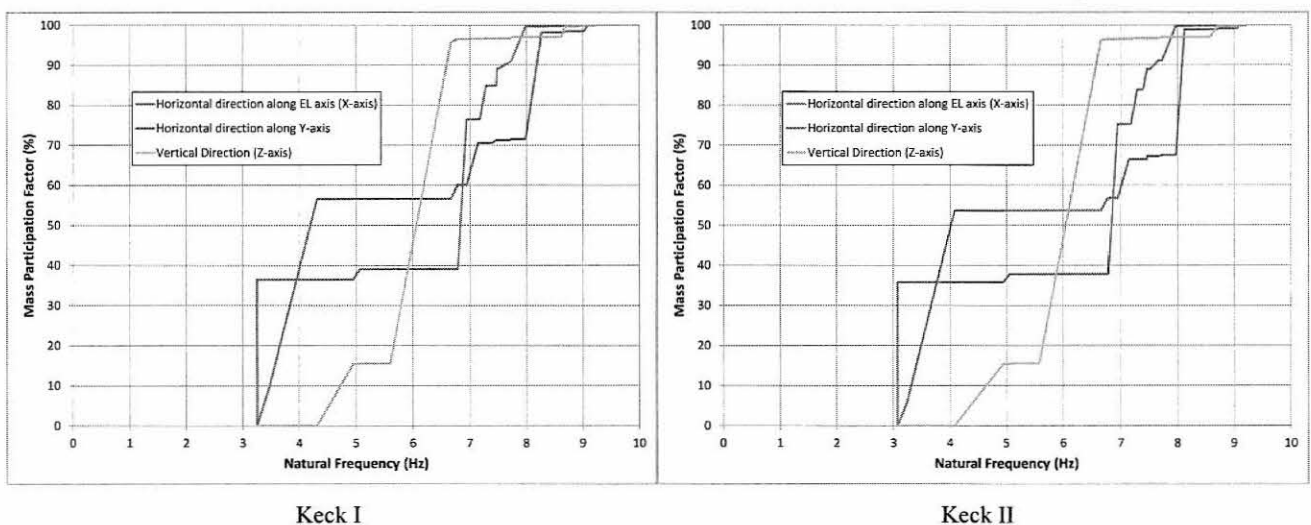


Figure 10. Cumulative Mass Participation Factors for Keck I and Keck II at EL=90°

7. TIME HISTORY ANALYSIS FOR SURVIVAL-LEVEL EARTHQUAKE

Time history analyses were performed to compute the dynamic responses of Keck I and Keck II Telescopes for survival-level earthquake by subjecting the model to the seven sets of time histories described in Section 2. The analyses were performed with the telescopes at elevation angles 0°, 60°, and 90°. For each elevation angle, two azimuth orientations were analyzed. The first orientation is with the east-west ground accelerations aligned with the global X-axis of the telescope model and the north-south ground accelerations aligned with the global Y-axis. The second orientation is with the east-west ground accelerations aligned with the global Y-axis and north-south ground accelerations aligned with the global X-axis. 2% Rayleigh damping was used in the time history analyses for survival-level earthquake. A total of eighty-four analyses were performed (two models: Keck I and Keck II; three elevation orientations: 0°, 60°, and 90°; two azimuth orientations: EW in X and EW in Y; and seven time histories).

Tables 5 through 8 summarize the peak dynamic responses from the time history analyses for survival-level earthquake. Additional results for each time history case are provided in [11].

In general, the average seismic responses from the survival-level earthquake time history analyses are roughly equal to those obtained from the response spectrum analyses. Seismic responses from survival-level earthquake time history analyses are about 2 times those from the 2006 Mauna Kea Earthquake.

Table 5. Peak Accelerations (g) at Various Locations on Keck I and Keck II Telescope Structure

	Telescope	Elevation	Damping	Primary Mirror	Nasmyth Platform	Cassegrain Socket	Tertiary Mirror Socket	Secondary Mirror Socket
Response Spectrum Analysis	Keck I	0°	0.5%	4.8	6.5	5.3	5.3	6.9
			2.0%	3.6	4.9	4.0	3.9	5.1
		60°	0.5%	5.4	6.3	6.1	5.9	5.8
			2.0%	4.0	4.7	4.5	4.4	4.3
		90°	0.5%	5.6	6.3	6.3	6.1	5.8
			2.0%	4.2	4.7	4.7	4.5	4.3
	Keck II	0°	0.5%	4.8	6.4	5.2	5.3	6.4
			2.0%	3.6	4.8	3.9	4.0	4.8
		60°	0.5%	5.4	6.2	6.0	6.0	5.1
			2.0%	4.1	4.6	4.5	4.4	3.8
		90°	0.5%	5.6	6.2	6.2	6.1	5.1
			2.0%	4.2	4.6	4.6	4.6	3.8
Time History Analysis 2006 Hawaii EQ	Keck I	0°	0.5%	2.1	4.1	2.5	2.7	3.1
			2.0%	1.3	2.6	1.3	1.9	1.5
	Keck II	0°	0.5%	2.1	3.0	2.3	2.2	2.3
			2.0%	1.8	2.3	1.9	1.9	1.9
Time History Analysis Survival Level Earthquake	Keck I	0°	2.0 % Min.	2.4	3.8	2.5	2.8	3.9
			2.0 % Max.	4.0	6.1	4.8	4.5	6.3
			2.0 % Avg.	3.1	4.6	3.4	3.8	4.7
		60°	2.0 % Min.	3.0	3.8	3.4	3.3	3.0
			2.0 % Max.	6.0	7.3	6.6	7.1	5.7
			2.0 % Avg.	3.8	4.7	4.3	4.3	4.0
		90°	2.0 % Min.	3.1	3.8	3.5	3.3	3.0
			2.0 % Max.	6.6	8.0	7.3	7.5	5.8
			2.0 % Avg.	4.0	4.8	4.5	4.6	3.9
	Keck II	0°	2.0 % Min.	2.5	3.6	2.6	2.7	3.5
			2.0 % Max.	4.0	5.9	4.5	4.7	5.1
			2.0 % Avg.	3.2	4.5	3.3	3.8	4.1
		60°	2.0 % Min.	3.1	3.8	3.2	3.0	2.3
			2.0 % Max.	6.3	6.7	7.1	6.5	3.5
			2.0 % Avg.	3.9	4.6	4.3	4.4	3.0
		90°	2.0 % Min.	3.2	3.8	3.4	3.1	2.2
			2.0 % Max.	6.6	7.1	7.5	6.7	3.5
			2.0 % Avg.	4.1	4.6	4.6	4.7	2.9

Table 6. Peak Displacement (mm) at Various Locations on Keck I and Keck II Telescope Structure

	Telescope	Elevation	Damping	Primary Mirror	Nasmyth Platform	Cassegrain Socket	Tertiary Mirror Socket	Secondary Mirror Socket
Response Spectrum Analysis	Keck I	0°	0.5%	76	78	31	76	104
			2.0%	57	58	23	56	77
		60°	0.5%	76	78	26	77	107
			2.0%	57	57	19	57	80
		90°	0.5%	76	78	19	77	108
			2.0%	57	57	14	58	80
	Keck II	0°	0.5%	82	83	28	82	104
			2.0%	61	62	21	61	77
		60°	0.5%	83	83	24	84	105
			2.0%	62	61	18	62	78
		90°	0.5%	83	83	19	84	105
			2.0%	62	61	14	63	79
Time History Analysis 2006 Hawaii EQ	Keck I	0°	0.5%	35	41	24	37	45
			2.0%	22	25	11	23	27
	Keck II	0°	0.5%	34	35	14	35	39
			2.0%	31	30	12	33	32
Time History Analysis Survival Level Earthquake	Keck I	0°	2.0 % Min.	28	40	16	31	45
			2.0 % Max.	63	70	38	67	84
			2.0 % Avg.	48	52	27	49	64
		60°	2.0 % Min.	37	39	11	32	52
			2.0 % Max.	71	85	25	75	82
			2.0 % Avg.	49	54	21	52	66
		90°	2.0 % Min.	37	39	10	35	53
			2.0 % Max.	76	88	22	78	79
			2.0 % Avg.	50	54	16	53	66
	Keck II	0°	2.0 % Min.	32	39	16	33	43
			2.0 % Max.	65	72	32	67	69
			2.0 % Avg.	50	54	22	52	58
		60°	2.0 % Min.	36	45	12	35	36
			2.0 % Max.	85	86	27	83	79
			2.0 % Avg.	53	57	19	56	57
		90°	2.0 % Min.	39	46	10	36	37
			2.0 % Max.	91	90	22	86	77
			2.0 % Avg.	55	58	16	57	56

Table 7. Peak Force (kN) in Various Components on Keck I and Keck II Telescope Structure

	Telescope	Elevation	Damping	AZ Hydrostatic Support	Earthquake Safety Bracket	Combined Bracket	AZ Drive	Hydrostatic Vertical Support
Response Spectrum Analysis	Keck I	0°	0.5%	1,046	859	--	700	3,826
			2.0%	778	640	--	521	2,849
		60°	0.5%	1,024	850	--	663	3,784
			2.0%	762	633	--	493	2,819
		90°	0.5%	1,027	853	--	666	3,755
			2.0%	765	635	--	495	2,798
	Keck II	0°	0.5%	--	--	1,090	1,131	3,841
			2.0%	--	--	813	843	2,867
		60°	0.5%	--	--	1,081	1,099	3,796
			2.0%	--	--	807	819	2,834
		90°	0.5%	--	--	1,083	1,102	3,773
			2.0%	--	--	808	821	2,818
Time History Analysis 2006 Hawaii EQ	Keck I	0°	0.5%	762	633	--	505	2,892
			2.0%	444	368	--	306	1,608
	Keck II	0°	0.5%	--	--	616	700	2,254
			2.0%	--	--	483	518	1,763
Time History Analysis Survival Level Earthquake	Keck I	0°	2.0 % Min.	746	515	--	496	2,496
			2.0 % Max.	1,591	1,071	--	1,052	5,041
			2.0 % Avg.	979	706	--	658	3,563
		60°	2.0 % Min.	805	590	--	513	2,935
			2.0 % Max.	1,992	1,255	--	1,357	5,832
			2.0 % Avg.	1,042	755	--	685	3,660
		90°	2.0 % Min.	804	609	--	510	2,931
			2.0 % Max.	2,001	1,278	--	1,347	5,695
			2.0 % Avg.	1,055	766	--	688	3,620
	Keck II	0°	2.0 % Min.	--	--	665	748	2,526
			2.0 % Max.	--	--	1,294	1,470	4,555
			2.0 % Avg.	--	--	929	1,032	3,561
		60°	2.0 % Min.	--	--	691	817	2,298
			2.0 % Max.	--	--	1,750	2,093	5,822
			2.0 % Avg.	--	--	995	1,130	3,662
		90°	2.0 % Min.	--	--	736	821	2,525
			2.0 % Max.	--	--	1,784	2,153	5,909
			2.0 % Avg.	--	--	1,005	1,134	3,660

Table 8. Peak Elastic Strain (%) in Various Components on Keck I and Keck II Telescope Structure

	Telescope	Elevation	Damping	AZ Hydrostatic Support	Earthquake Safety Bracket	Combined Bracket
Response Spectrum Analysis	Keck I	0°	0.5%	0.78%	0.22%	--
			2.0%	0.58%	0.17%	--
		60°	0.5%	0.76%	0.22%	--
			2.0%	0.57%	0.17%	--
		90°	0.5%	0.76%	0.22%	--
			2.0%	0.57%	0.17%	--
	Keck II	0°	0.5%	--	--	1.65%
			2.0%	--	--	1.23%
		60°	0.5%	--	--	1.64%
			2.0%	--	--	1.22%
		90°	0.5%	--	--	1.64%
			2.0%	--	--	1.22%
Time History Analysis 2006 Hawaii EQ	Keck I	0°	0.5%	0.57%	0.17%	--
			2.0%	0.33%	0.10%	--
	Keck II	0°	0.5%	--	--	0.93%
			2.0%	--	--	0.73%
Time History Analysis Survival Level Earthquake	Keck I	0°	2.0 % Min.	0.56%	0.13%	--
			2.0 % Max.	1.18%	0.28%	--
			2.0 % Avg.	0.73%	0.18%	--
		60°	2.0 % Min.	0.60%	0.15%	--
			2.0 % Max.	1.48%	0.33%	--
			2.0 % Avg.	0.78%	0.20%	--
		90°	2.0 % Min.	0.60%	0.16%	--
			2.0 % Max.	1.49%	0.33%	--
			2.0 % Avg.	0.79%	0.20%	--
	Keck II	0°	2.0 % Min.	--	--	1.01%
			2.0 % Max.	--	--	1.96%
			2.0 % Avg.	--	--	1.41%
		60°	2.0 % Min.	--	--	1.05%
			2.0 % Max.	--	--	2.65%
			2.0 % Avg.	--	--	1.51%
		90°	2.0 % Min.	--	--	1.12%
			2.0 % Max.	--	--	2.70%
			2.0 % Avg.	--	--	1.52%

8. DISCUSSION

- The calculated natural frequencies of the first elevation mode and the first azimuth mode compare fairly well with the measured frequencies obtained from the Keck I servo identification study results.
- Results from the time history analyses for the 2006 Mauna Kea Earthquake show very high strains in the Hydrostatic Radial Supports in Keck I and the Earthquake Safety Corners in Keck II. If plasticity were included in the model, these components would have had permanent deformation. The strains in the Keck I Earthquake Safety Brackets are much less. Analysis predicts very little to no yielding in the Earthquake Safety Brackets. These results are consistent with the observed damage.
- The calculated travels at the azimuth track for the 2006 Mauna Kea Earthquake are much less than the observed values of 11 mm because material plasticity and contact interaction at the supports were not included in the model.
- Peak seismic responses computed from response spectrum analysis for 0.5% damped structure are approximately 1.3 times higher than those for 2% damped structure.
- Peak seismic responses of Keck I are about the same as those of Keck II.

- Peak seismic responses of the elevation structure change with elevation angle.
- Seismic responses from the survival-level earthquake time history analyses are roughly equal to those obtained from the response spectrum analyses.
- Peak accelerations from a survival-level earthquake is estimated to be about 4 to 5 g at secondary mirror socket and Nasmyth platform at the instrument support, 3.5 to 4.5 g at Cassegrain socket and Tertiary Mirror socket, and 3 to 4 g at the Primary Mirror.
- Results show that a survival-level earthquake will cause damage to the Keck I Hydrostatic Radial Supports and Earthquake Safety Brackets, and the Keck II Combined Brackets.
- Seismic responses from survival-level earthquake time history analyses are about 2 times those from the 2006 Mauna Kea Earthquake.
- The finite element models developed here should be used to evaluate alternate seismic restraint design options.

9. CONCLUSIONS

Finite element models of Keck I and Keck II Telescopes were developed. The models were validated using the servo identification study results and the 2006 Mauna Kea Earthquake observations. Preliminary response spectrum and time history analyses were performed to predict the responses of the telescope structure to a survival-level earthquake. These two finite element models should be used to evaluate alternate seismic restraint design options.

10. ACKNOWLEDGEMENTs

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REFERENCES

- [1] ANSYS Mechanical APDL Release 14.0, ANSYS, Inc.
- [2] "Soil Investigation, Keck Observatory 10-Meter Telescope, Mauna Kea, Hawaii," Harding Lawson Associates, HLA Job No. 2313,049.04 (22 Nov. 1985).
- [3] "Foundation Deflection During rotation of Telescope, W. M. Keck Observatory, Mauna Kea, Hawaii," Harding Lawson Associates, HLA Job No. 2313,047.06 (7 Jan. 1987).
- [4] Sieffert J-G. and F. Cevaer, [Handbook of Impedance Functions – Surface Foundations], Ouest Editions, Presses Academique (1992).
- [5] Nelson, J. E., T. S. Mast, and S. M. Faber, "The Design of the Keck Observatory and Telescope," Keck Observatory Report, 90. The University of California and California Institute of Technology (1985).
- [6] Hawaii County Code 1983, Chapter 5 Building, 2005 Edition with Supplement 14 (July 2012).
- [7] [International Building Code 2006], International Code Council (2006).
- [8] [Minimum Design Loads for Buildings and Other Structures (7-05)], American Society of Civil Engineers (2005).
- [9] Newmark, N.M. and W.J. Hall, "Earthquake Spectra and Design," Earthquake Engineering Research Institute, Berkeley, CA, 35-36 (1982).
- [10] "Site-Specific Seismic Hazard Assessment of Proposed Thirty Meter Telescope Site, Mauna Kea, Hawaii," URS Corporation, URS Job No. 33761857 (4 Feb. 2010).
- [11] "Keck I & Keck II Telescopes FEM Development and Preliminary Seismic Analyses," Simpson Gumpertz & Heger, SGH Project No. 110455 (11 October 2012).